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ORIGINAL ARTICLE

Towards farm-level health management of offshore wind farms for maintenance improvements

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Abstract This paper studies a conceptual architecture for health management of offshore wind farms. To this aim, various necessary enablers of a health management system are presented to improve reliability and availability while optimizing maintenance costs. The main focus lies on improving existing condition monitoring systems based on concepts of condition-based maintenance and reliability centered maintenance. A brief review of the relevant state-of-the-art is presented and gaps to be filled towards realization of such health management system are discussed.

Keywords Health management · Offshore wind farm · Maintenance

1 Introduction

Renewable energy sources are gaining importance due to depleting fossil fuel reserves and their adverse environmental impact. The European Union (EU) aims to shift 20 % of its energy reliability to renewable energy resources by 2020 and the European Wind Energy Association (EWEA) estimates about 14 % of this to be fulfilled by wind energy [1]. Higher wind energy production translates to larger wind farms and higher capacity turbines. Offshore wind farms (OWFs) have become popular because of abundance of wind source, savings on valuable real-estate and little impact of wind turbine (WT) noise.

Although OWFs are advantageous in many ways, their availability is still not comparable to their onshore counterparts. It was found that while the onshore availability is reaching 99 %, the OWFs for the UK at *Barrow North*, *Hoyle*, *Kentish Flats* have availability figures between 67 and 85 % [2]. The downtimes are longer because of the finite weather windows in which personnel can perform the required maintenance. Besides, the maintenance costs are also comparatively higher at the range of 18–23 % of the life cycle costs owing to their location and associated difficulty of maintenance [3].

It is now well accepted that condition monitoring (CM) is important in predicting failures in remotely located WTs both by the wind farm operators and insurance companies [4]. Health monitoring, condition-based maintenance (CBM) and reliability centered maintenance (RCM) are established areas in aerospace sectors and well-proven in energy, oil and gas sectors. Often, these techniques are borrowed in providing a solution in wind energy sector with necessary modifications. It is worthwhile to note that unlike other sectors, equipment in OWFs has to withstand a highly corrosive offshore environment, bad weather conditions like storms and non-stationary operating profiles.

Given the understanding about the importance of CM and need for effective maintenance strategies for wind farms, a substantial amount of research has been performed through

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collaboration between industry and academia. ECN's CONMOW [5], ReliaWind [6] and Supergen [7] are some of the notable efforts undertaken by European research consortia for WT condition monitoring. Some of the significant surveys on operation and maintenance data of wind farms have appeared in Ribrant et al. [8] on Swedish wind farms, Hahn et al. [9] on German wind farms, and ReliaWind [6] on turbines across EU, wherein the most frequent failures and their corresponding downtimes were identified. Besides, ReliaWind program made substantial contributions such as a WT taxonomy, which is now generally accepted as well as the identification of high priority failure modes for various WT subsystems [10].

Due to the widespread acceptance of CM for wind farms, there are now a variety of commercial CM systems that are offered by original equipment manufacturers (OEMs), turbine operators, and third parties. A recent research claims that there are as many as 36 different products on the market [11] but almost all of these target generator, drive train, main bearings and blades.

Bussell [12] proposes that in a typical onshore wind farm of 120 units of 2MW turbines, an average of 600 maintenance visits is necessary per year. Even if one optimistically assumes that CM systems that are commercially available are installed, they cover only a subset of the WT subsystems and the balance-of-system (BoS) is still dependent on reactive or scheduled maintenance. It may be possible to conduct reactive maintenance for the onshore wind farms, but in case of OWFs, this could become extremely difficult due to weather windows, transportation costs, and would involve higher down times due to their location. However, studies conducted by Nilsson et al. [13] in 2007 and National Renewable Energy Laboratory (NREL) [14] in 2010 claim that scheduled maintenance is still the norm with wind farms and service is usually conducted once to twice a year.

In order to achieve better availability while reducing maintenance costs of OWFs, it is necessary to adapt a farm-level maintenance strategy, which also includes economizing on maintenance logistics, resources, and inventory. While the condition monitoring is the knowledge of whether the system is healthy or faulty, the health management is the capability to make intelligent, informed, appropriate decisions about maintenance and logistics actions based on diagnostics and prognostics information, available resources, and operational demand [15]. It is improving from the model of utilizing CM systems as end products in maintenance decision process to a system-level solution that handles maintenance of the whole wind farm, depending on the health of the wind turbines.

The main contribution of this paper is to present a conceptual architecture for farm-level health management of offshore wind farms and explain the necessary enablers. It is designed considering the specific constraints for offshore wind farms. The proposed architecture aims to support maintenance, resource, and inventory planning based on the asset health and failure predictions. Furthermore, the architecture is utilized to gain a system-level understanding of the maintenance scheme, determine the scope of each element, and the gaps to be filled in order to realize such a health management system.

The rest of this paper is organized as follows. Section 2 briefly describes the CBM and RCM strategies and presents a comprehensive maintenance strategy for wind farms. Farm-level health management architecture based on CBM and RCM is presented in Section 3, explaining the elements involved. Further discussions on some issues, challenges, and gaps related to health management of offshore wind farms are provided in Section 4 followed by Section 5, which concludes the work.

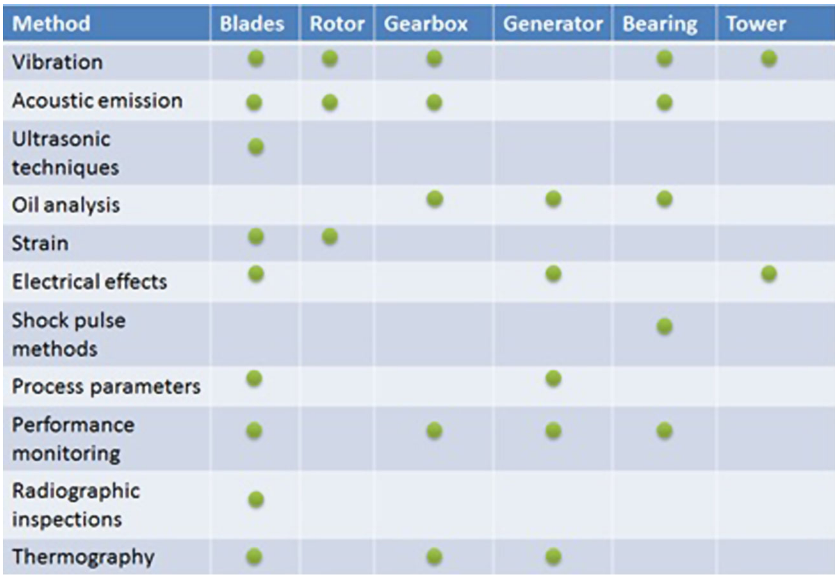
2 Maintenance methodologies

Maintenance in offshore wind farms (OWFs) is usually taken care of by wind turbine manufacturers within the period of the first 1 to 5 years after the installation. After this period, the maintenance is performed by either the operator, third parties, or maintenance contract with the OEMs are extended. The maintenance mainly comprises of two types, (1) scheduled maintenance, wherein maintenance is done either based on calendar (time) or number of operating hours; and (2) reactive maintenance, wherein maintenance is done upon a failure.

However, many of the wind farms are now equipped with CM systems along with the supervisory control and data acquisition (SCADA) systems for operation. As it was earlier estimated that gearbox and drive train together comprise up to 42 % of the total downtime [16], these systems have received great attention in terms of condition monitoring research. Consequently, a number of methods targeting diagnostics for generator, gearbox, and bearings have been developed primarily based on vibration sensing, temperature monitoring and oil debris analysis. CM systems for WT blades have been developed based on strain sensing, fiber optics, and ultrasound. An elaborate review of the existing CM systems for WTs can be found in reviews by Garcia Marquez et al. [17] and Takoutsing et al. [18], summarized in Fig. 1. It may be noticed, the balance of system components like pitch and yaw systems have not received much attention so far.

CM systems in wind farms often operate independently from the SCADA system. The maintenance personnel receive alarms based on asset condition and then maintenance task is manually determined. The advantage of existing CM systems can be fully realized only when they

Fig. 1 CM techniques for WTs: state-of-the-art



Method	Blades	Rotor	Gearbox	Generator	Bearing	Tower
Vibration	●	●	●		●	●
Acoustic emission	●	●	●		●	
Ultrasonic techniques	●					
Oil analysis			●	●	●	
Strain	●	●				
Electrical effects	●			●		●
Shock pulse methods					●	
Process parameters	●			●		
Performance monitoring	●		●	●	●	
Radiographic inspections	●					
Thermography	●		●	●		

contribute actively and systematically in maintenance planning. In order to achieve this, a comprehensive farm-level maintenance strategy is necessary.

2.1 Condition-based maintenance

CBM originated in the aerospace industry in order to reduce maintenance costs due to excessive scheduled maintenance. In essence, it follows the idea of “if it’s not broken, don’t fix it.” The condition of the equipment is monitored using CM systems that detect an *incipient* failure and subsequently a maintenance task is identified. CBM by itself does not give any guideline on which maintenance task to be performed and how to plan such maintenance in order to optimize the maintenance activities. The CBM concepts were standardized by MIMOSA as open system architecture for condition-based maintenance (OSA-CBM), which covers the functional blocks [19], as shown in Fig. 2. It is shown that the diagnostics and prognostics functions can support in *advisory generation* that could be used in either deferring a scheduled maintenance task or in performing a maintenance task to avoid an impending failure.

A majority of the developed diagnostics for WTs can be utilized for CBM. However, prognostics for rotating machinery is still a nascent area due to the complexity of the problem and variables involved [20].

2.1.1 CBM candidate selection

Condition monitoring is suitable for components that have sufficient degradation period. That is, from the time the CM systems detect an incipient failure or a *potential failure*, there should be sufficient time before *functional failure* to occur. Only then, a maintenance action can be executed and the failure averted. Also, it is important to assess whether CBM is a feasible solution for the component at hand, technically as well as monetarily. The following questions may be considered [21] for technical feasibility assessment:

- Is the failure mode observable through CM?
- Do state-of-the-art diagnostics and prognostics methods exist?

Fig. 2 OSA-CBM architecture

- Are the sensors and SCADA data already available for the diagnostics and prognostics?
- If additional sensors are necessary, is it possible to install them?
- Are the accuracy and reliability of the diagnostics and prognostics acceptable?
- Does CM reduce the risk of failure to an acceptable level?

After a successful analysis of technical feasibility is performed, cost-benefit analysis may be conducted. The cost of development of algorithms, sensors, installation, and setup costs as well as the maintenance (if any required) of CM systems should be considered during this time. Only when these requirements are satisfied, does it justify to implement CBM for the system under consideration. Stringent technical feasibility tests are necessary as it has been shown that high false alarm rates would alter the cost-benefit analysis of CBM systems [22].

2.2 Reliability centered maintenance

Of the various maintenance methodologies, RCM is considered most suitable for fleet-level health management. RCM focuses on ensuring overall availability of the system by choosing the most appropriate maintenance task for each fault condition. Originally developed in the aerospace sector [23], with a simple objective to *preserve system function*, it was later successfully applied in a variety of industries like energy, oil and gas, chemical industries, for instance.

RCM breaks the system down into components and then identifies the *key failure modes* that could result in functional failure. Once the failure modes are identified at subsystem and component levels, appropriate maintenance tasks are chosen per component and subsystem, based on their impact on safety and functionality of the system. Thus, RCM has the capability of zooming down to subsystem and component levels and back to system level. An RCM exercise, when correctly performed, results in a comprehensive maintenance plan for the system, tackling all the foreseeable failure modes and failures. SAE standards documents SAE JA-1011 [24], JA-1012 [21], NAVAIR 00-25-403 [25], and [26] are excellent resources for overall understanding of RCM process.

Broadly, the maintenance methods under RCM may be classified into reactive maintenance and proactive maintenance. The reactive maintenance includes a *run-to-fail* maintenance strategy for those subsystems that are not critical to safety or operation of the system. Proactive maintenance covers *scheduled restoration* or a *scheduled discard* tasks, which are chosen based on historical data of system performance and statistically determined mean time between failures (MTBF) for those systems that follow *bath tub curve* aging pattern. In system with variable failure patterns, *on-condition* maintenance is performed depending on the *PF-interval*.

RCM defines the early signs of potential failure as “an indication that a functional failure is about to occur or is in the process of occurring” and functional failure as that state where “a physical asset or a system is unable to perform a specific function to a desired level of performance” [21]. The time between a potential failure and functional failure is defined as the PF-interval as shown in Fig. 3.

The duration of PF-interval plays a significant role in maintenance planning. In this interval, a maintenance task has to be executed so that the availability of the equipment is maintained. In the case of CBM systems, the potential failure may be detected by the CM systems’ diagnostics. The potential failure may be due to aging or age-unrelated fault, which may result in accelerated degradation. After this stage, it is necessary to accurately quantify the fault and then predict the remaining useful life (RUL) or time to functional failure, that is, the PF-interval. Therefore, prognosis plays a very important role in maintenance planning and scheduling.

CBM may be classified as a predictive maintenance strategy that leads to an on-condition maintenance task in RCM process. Thus, CBM and RCM may be linked in the sense that RCM decides where CBM is practical and economically feasible maintenance option. While RCM gives the capability to zoom in to components of individual wind turbine, CBM gives the ability to continually observe the critical components the system.

2.3 Maintenance strategy for wind farms

In order to choose the right mode of maintenance, each subsystem of the WT should be analyzed at component level for functional failures. The ReliaWind program has identified a wind turbine taxonomy, which is now generally accepted

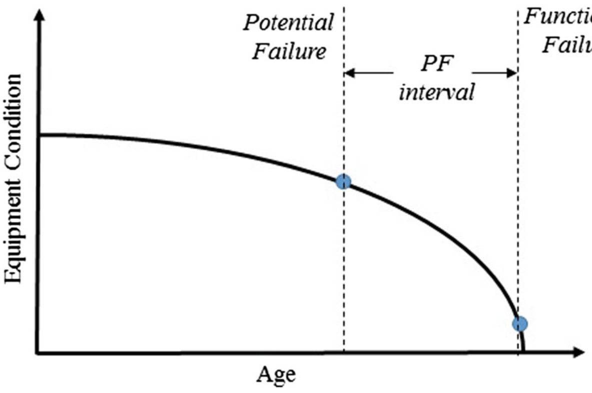


Fig. 3 P-F interval

in the wind turbine industry [10]. This taxonomy can be utilized for identification of key failure modes and appropriate maintenance procedures for the wind turbine systems. It should also be verified whether CBM is the right choice and if not, then other maintenance methodologies may be considered, as shown in Fig. 4. This way, maximum benefit of CM systems may be realized.

The idea of utilizing RCM for WT maintenance is put forward in a number of recently published literature. Besnard et al. [27] describe the concept of "reliability centered asset management (RCAM)" that enhances the concepts of RCM with quantitative maintenance optimization in order to quantify a particular maintenance choice. Igba et al. [28] take a "systems approach" for implementing RCM for gearboxes. Mc Millan et al. [29] studied Danish concept of multi-MW onshore wind turbine towards RCM implementation and concluded that a "highly refined system of condition monitoring and maintenance management, similar to systems in aviation sector have to be rolled out." Baglee et al. [30] discuss application of RCM to WTs and explain usage of E-monitoring for this purpose. Dehghanian et al. [31–33] describe a comprehensive assessment of electrical systems for RCM implementation including critical system identification and an approach for cost benefit analysis.

Although there have been instances detailing implementation aspects of RCM for a selection of components in the literature, or a few select elements of RCM, to the authors' knowledge, little attention has been paid so far on realization of health management architecture for wind farms. Considering specific areas of the wind farm for RCM without a comprehensive view could lead to solutions that are incomplete or counterproductive as some of the functions or effects of faults may be overlooked [34].

By defining the health management architecture, it would be possible to clearly identify the functions of each element, gaps to be filled, key technical questions to be answered, and above all a system level understanding of maintenance scheme. This paper presents a conceptual architecture for farm-level health management. The authors intend to disclaim that technical specification of each element in such architecture is not detailed as it is beyond the scope of this article and also, to be fully realized. The intention is only to take a step closer to such a system.

3 Farm-level health management architecture

It is established that there exists a need for a farm-level health management especially for OWFs. In order to realize such a system, there are many elements that are to be accomplished. As it will be shown, research in wind energy community is heading in the right direction with majority of such areas being explored. However, the health management architecture as presented here involves maturation of each of the elements. Besides, it involves a substantial task of integrating all the elements. A conceptual architecture for fleet level health management is shown in Fig. 5. The objective of this architecture is to generate a maintenance plan and schedule for the next maintenance action, given the asset health and the existing constraints such as the availability of resources, transport vessels, weather windows, and pre-planning the inventory and logistics accordingly.

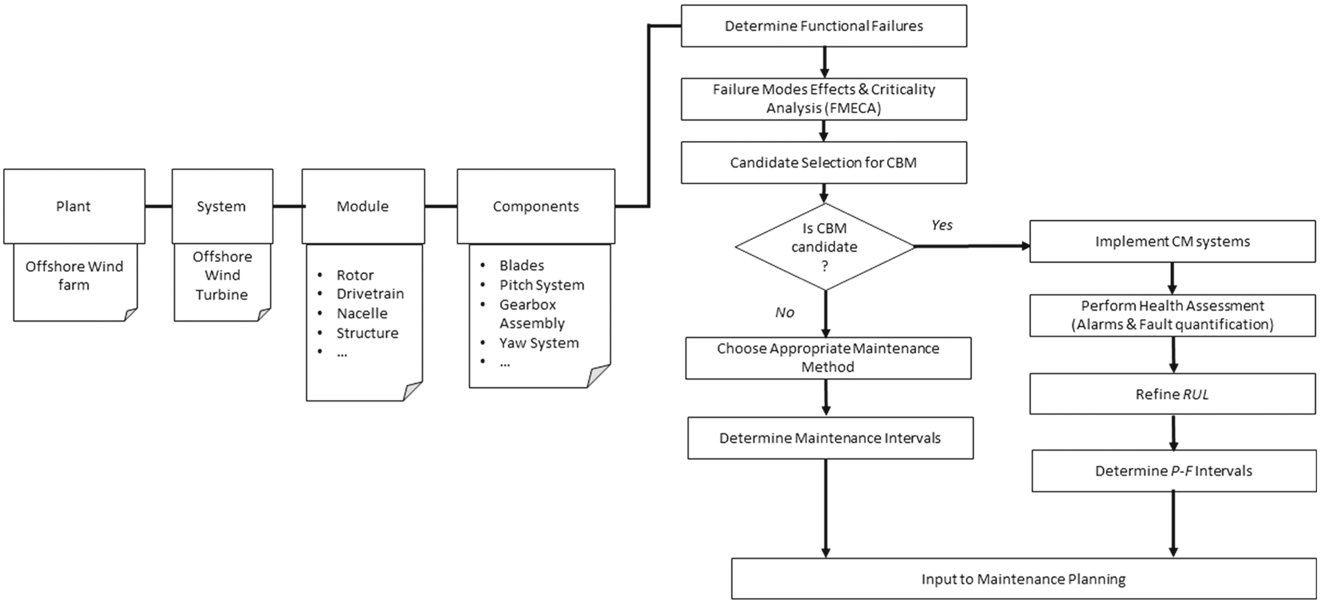


Fig. 4 Selection of suitable maintenance procedure for each component

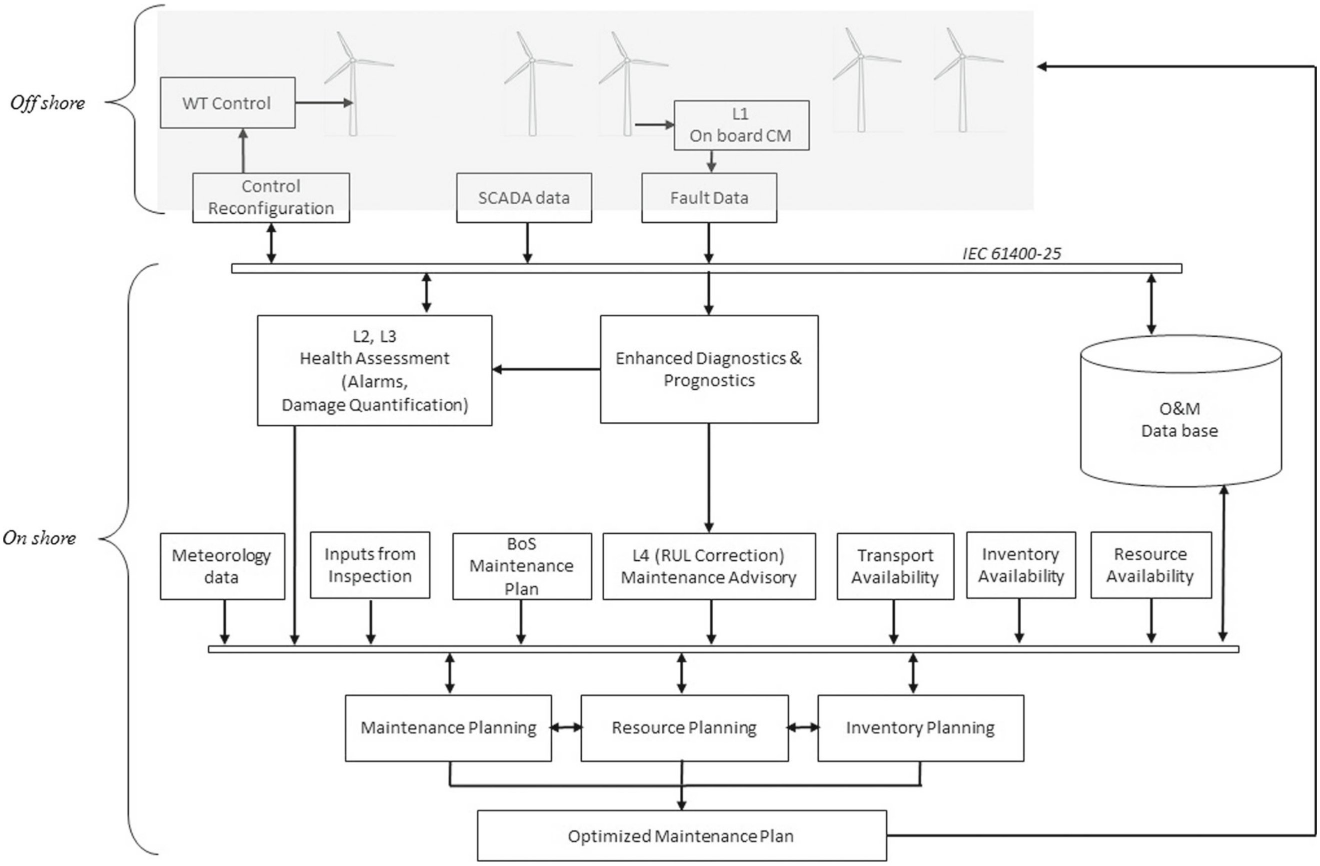


Fig. 5 Farm-level health management architecture

A few reasonable and practical assumptions are made during the process of development of the architecture as follows:

1. The wind farm has CM systems set up which may be independent from the SCADA systems.
2. The wind farm is connected to an onshore center that collects the SCADA operational data and CM data at their respective (time) resolutions.
3. The SCADA data and CM data from each wind turbine is transmitted reliably to the onshore operations center. Necessary protocols for secure error-free transmission and storage SCADA and CM data have been established.
4. The conventional maintenance procedures are sufficiently documented and each existing maintenance task is clearly identified.
5. The CBM candidate selection activity has been performed, suitable maintenance tasks against functional failures are identified, and RCM maintenance methodology is established.

Also, in the context of CBM, the diagnostics and prognostics information is classified into the following four stages as denoted in Fig. 5:

- L1 - Fault detection: The condition monitoring system is capable of differentiating between a healthy and faulty condition. At this stage, manual intervention is necessary to determine the fault.
- L2 - Fault diagnosis: The exact fault is identified and a suitable maintenance action may be determined. However, at this stage, there is no information on *when* the maintenance action is necessary.
- L3 - Fault quantification: The exact fault is identified and its magnitude is determined. At this stage, it is possible to determine whether *immediate* action is necessary.
- L4 - Fault prognosis: The exact fault is identified, its magnitude is determined and due course to critical stage is estimated with acceptable accuracy. The time to failure is identified and hence a maintenance window may be chosen.

The elements of the architecture are explained below.

3.1 On-board CM systems

At every individual WT level, the L1 information is available based on the CM systems. In diagnostic methods wherein high data rates from sensors are necessary such as acoustic emission (AE) techniques, it may be impractical to transfer data continuously, from each turbine to the onshore center. Hence preliminary analysis can be performed at WT level and only in case of anomalous behavior, data may be transmitted to the onshore center for enhanced diagnostics and prognostics analysis. Based on the RCM analysis, all those subsystems that are CBM candidates should be upgraded to CBM mode of maintenance. The remainder of the subsystems will be covered under scheduled or run-to-fail maintenance.

3.2 SCADA and fault data

As all the WTs are connected to the onshore center, it is ensured that the SCADA data is continuously available for all the WTs in the OWF. Depending on the nature of the CM system, the trip event data may be intermittent and supplied only upon incidents of faulty behavior. The capability of transferring, handling, and storing data must be analyzed a priori.

3.3 Communication protocol

Communication protocols constitute the crucial link between the offshore and onshore and can have direct impact on the maintenance decision making process. The communication protocols such as IEC-61400-25 provide a definite structure for data transmission from the turbines to the offshore center and hence avoid any ambiguity regarding the turbine as well as the type and location of the fault on the turbine. The IEC-61400-25 uses "logical device" for each WT and "logical nodes" for each zone of the turbine such as rotor, transmission, and generator for instance [35]. Thus, a fault within the yaw system of a particular WT for example, is communicated with the specific turbine and location information. An extension of the communication standard to incorporate additional tags for OWFs as specified in [36] may be considered while increasing the number of CM systems to be monitored.

3.4 Enhanced diagnostics and prognostics

The necessary fault diagnosis to determine exact fault post L1 stage information is performed at the onshore center. Onshore location is beneficial for enhanced diagnostics and prognostics as they are computationally intensivetasks that may require high performance computational resources and farm level operational data. Detailed analysis of fault based on diagnostics and prognostics algorithms should be performed at this stage to derive L2, L3, and L4 level information.

3.5 Operation and maintenance database

An operation and maintenance (O&M) database should be designed to hold SCADA operational data, meteorological data, fault data and maintenance logs for the OWF. Detailed requirements of such database should be finalized and used in design. Faulstich et al. [37] described a concept database for offshore WT analysis, that takes into account a number of factors beyond fault logs. This database stems from the German program Offshore Scientific Measurement and Evaluation Program (OWMEP). A slightly modified version of the database, primarily towards O&M use in an OWF is shown in Fig. 6.

Here, the core data is defined similar to that in [37, 38], as geographical and technical data of the turbines. The operational data is the continuous collection of SCADA data, of healthy turbine, and all fault events are collected in the event data. The meteorological and hydrological data consists of essential weather conditions like wind speed and wave height forecasts for the maintenance planning. The RCM data consists of the pre-defined maintenance tasks for all of the foreseen faults during RCM exercise and the associated procedures. The inventory data consists of detailed listing of the available spares and those that are ordered and to be delivered along with available time and quantity. Similarly, the vessel fleet data and resource data consists of the forecast of the transport vessels and resource availability for maintenance planning. All the information as shown in Fig. 6 should be available online in an easily retrievable manner for intelligent maintenance plan generation.

Data quality is an important issue to be considered at this stage. Data transfer from the offshore to the onshore location may entail data losses, erroneous data, and missing data. Therefore, data must be assessed before it is transferred to the database. Data cleaning, quality assessment, and missing data reconstruction may be considered using established approaches such as artificial intelligence techniques [39] and advanced estimation based methods for non-uniformly sampled systems [40].

3.6 Health assessment

The L2 and L3 level information derived using enhanced diagnostics and prognostics is used to generate alerts for maintenance planning. Also, the fault quantification information may be utilized for control reconfiguration purposes [41]. Advanced control techniques such as damage-mitigating controls [42], with the objective of extending life while attaining near-optimal performance may be considered for wind turbines.

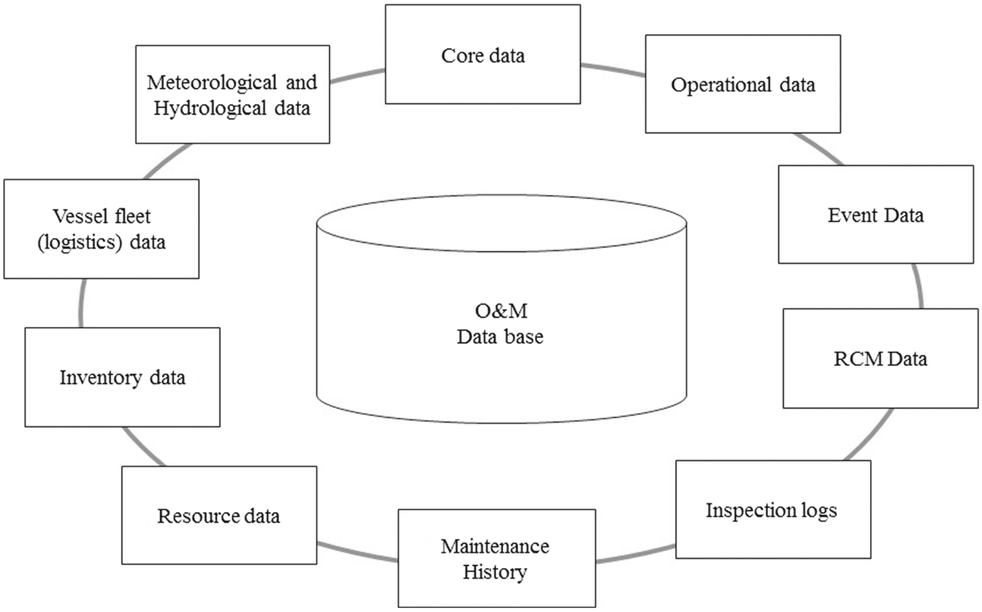


Fig. 6 A database for farm-level health management

3.7 Maintenance advisory

The RUL for CBM candidates is determined by the prognostics algorithms based on their current health status and fault quantification. This information may override the RUL derived from design or historical data and hence refines the PF-intervals. The modified subsystem level RUL information (L4) for all WT's in the OWF is provided to the maintenance planning regularly based on the evident fault.

3.8 Maintenance, resource, and inventory planning

The maintenance planning for OWF should be a living process. Depending on the alarms from the CM systems and the modified RULs that are supplied, the maintenance plans should be updated regularly. It has been shown that there exists opportunity for significant savings if two different WT maintenance tasks are clubbed and conducted at the same time [13]. The maintenance, resource, and inventory planning are interlinked and should be considered in that way for optimization. Adhikari et al. [43] describe the linkage between maintenance and resource management in aerospace scenario. Besides, for OWFs, there are a number of factors that are to be considered for efficient maintenance planning that are particularly unique to this area. Resource planning entails location of the maintenance crew, work shifts, and number of maintenance teams as well as planning of transport vessels and helicopters and availability of spares [44–47]. Weather window forecasting is another important factor for determining maintenance schedules [48].

Although RCM exercise reveals the most suitable maintenance task for the given failure mode, it does not in itself determine the maintenance schedules or task prioritization. This has to be accomplished using methodologies like risk-based maintenance (RBM) [49, 50] or opportunistic maintenance methods [51–53]. ECN's OMCE [54] and SINTEF's NOWICOB [55] are notable tools for assisting maintenance planning by estimating cost of maintenance scenario that have provision to include the constraints.

At this stage, the outcome should be the schedule for the next maintenance action and the necessary maintenance tasks to be accomplished in that maintenance exercise. The generated maintenance plan is sensitive to equipment health (updated RUL) and constraints such as the weather windows, inputs from previous manual inspections, balance-of-system's scheduled maintenance tasks, resource availability, and logistics. Thus, the health management architecture ensures high availability of the wind farm while economizing on the maintenance costs.

4 Issues, challenges, and gaps

Wind sector has the advantage of being younger compared to the conventional energy sector and this should be fully utilized by adapting the best practices and know-how from the energy and aerospace sector at the early stages of offshore wind farms. Aspects like design for maintainability and reliability have to be given due consideration in design phase of the future WTs. Thorough and systematic analysis of the existing WT operational data and maintenance tasks will provide insights into aspects of the WTs that require design level changes towards improving reliability.

Although some of the areas of such a systematic maintenance are receiving attention in terms of research and development, there are certain gaps to be filled.

4.1 Standards, guidelines, and requirements

An offshore wind farm can include WTs from different manufactures and CM systems that run on proprietary software, which lack architectural commonalities. This can pose major problems in generalizing maintenance approach for OWFs. Although IEC 61400-25 [35] aims at standardizing the communications protocols, it is still dependent on the OWF and WT manufacturers, to decide at what level of the system do they choose to apply the communication standard [56, 57]. Besides, National Renewable Energy Laboratory (NREL) claims that the existing standards of IEC-61400 family are inadequate and to be modified for American offshore implementation [58]. They claim that the European establishments complement the standards with guidelines from DNV [59], and GL [60], which are customized for the local use. Also, the existing guidelines for certification of CM systems [61] are primarily focused on vibration sensing and a limited set of subsystems namely, drivetrain, main bearing, generator, nacelle, and blades.

While standards for health management are still in preparation even in aerospace sector [62], where research was being conducted for the past two decades, it is worthwhile to consider development in wind energy sector.

In order to realize an effective farm-level maintenance strategy, it becomes necessary to follow a system engineering methodology. Various stakeholders have to be identified and the requirements of health management to be clearly defined. The elements of health management may be deployed in a modular fashion with suitable verification and validation against the identified system-level requirements. Finally, it must be noted that RCM itself is a “living process” and the developed system must be capable of accommodating future extensions for newer components, diagnostics and prognostics methods or changes in the maintenance method for components depending on their behavior through their lifetime.

4.2 Database creation and maintenance

The database mentioned in Section 3.5 involves significant efforts towards development and maintenance. Tasks such as standardization of data, efficient and error-free transfer of data to and from the database, standard maintenance, and inspection logging formats based on the fault category, level, and the equipment break-down structure are to be framed and strictly followed. This requires considerable resources, both in terms of personnel and infrastructure, and should be accounted for during the planning of the health management scheme.

4.3 Advances in prognostics

Fault quantification and prognostics are currently at a nascent phase. There have been attempts in data-driven as well as model-based approaches to determine the damage accumulation but until now, there is no single standard approach that has been reliably proven to perform consistently well, owing to the complexity of the problem as well as the time required to simulate such failures. Especially for OWFs, it has been noted that corrosion and associated fatigue wear play a significant role in equipment failure not only for the structure but also the nacelle components [63]. These problems have to be addressed by prognostics in order to accurately predict the RULs for the CBM candidates and aid in effective maintenance planning. Also, capturing the effects of external factors such as a maintenance task performed or a lubrication task on the RUL predictions is still an open question. Besides, reliability of the developed prognostics methods is to be assessed before incorporating the results into maintenance decision making process. Metrics for qualifying prognostics methods such as described by Saxena et al. [64] are required for accuracy assurances.

4.4 Focus on balance-of-system

As it has been discussed earlier, the current CM systems are predominantly focused on drive train, main gearbox, generator, and blades. There are also other modules of the WT that have been reported to have significant failure rates and down times such as yaw and pitch systems, electronics components, etc. RCM strategy is a comprehensive approach to maintenance and during its application each module of the system should be carefully examined. The balance-of-system candidates should be evaluated following CBM candidate selection procedure as described in Section 2.1.1 and suitable maintenance strategy should be finalized through an RCM exercise.

5 Conclusion

As the wind farms are getting larger, it becomes a necessity to adopt a farm-level maintenance strategy. Health management, derived with RCM and CBM as basis, appears to be the most suitable approach for farm-level implementation. Health management is one of the advanced maintenance solutions developed in the aerospace sector and owing to the nature of the industry, is scalable and designed for fleet-level implementation.

In this paper, an attempt was made towards development of such health management architecture for wind farms considering the constraints specific to offshore wind energy. The architecture is then used to identify the necessary elements, scope of the elements, and the gaps to be filled before integrating them. A number of research efforts in the wind energy community that can be leveraged in development of such health management solution were highlighted and discussed. However, it is necessary to prove that such architecture would result in the availability and cost benefits it claims. This is a major task as it involves development of clear specifications of each of the elements in the architecture and their integration. The authors intend to develop a simulation framework considering the various aspects discussed in this architecture and quantify the benefits in terms of availability and cost savings in the future work.

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